International Workshop on
Structual Formation and Selection Rule
in Turbulent Plasmas
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Issues in Integrated Transport Codes

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Contents

- TASK: **T**ransport **A**nalysing **S**ystem for tokama**K**
- TASK/TR: Diffusive Transport Simulation
- TASK/TX: Dynamical Transport Simulation
- TASK2005: Documentation
- Summary

TASK Code

- Transport Analysing System for TokamaK
- **Features**
  - **A Core of Integrated Modelling Code in BPSI**
    - Modular Structure
    - Reference Data Interface
  - **Various Heating and Current Drive Scheme**
    - EC, LH, IC, AW, (NB)
  - **High Portability**
    - Most of Library Routines Included (except LAPACK and MPI)
    - Own Graphic Libraries (gsaf, gsgl)
  - **Development using CVS** (Concurrent Version System)
    - Open Source (by the end of 2004)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

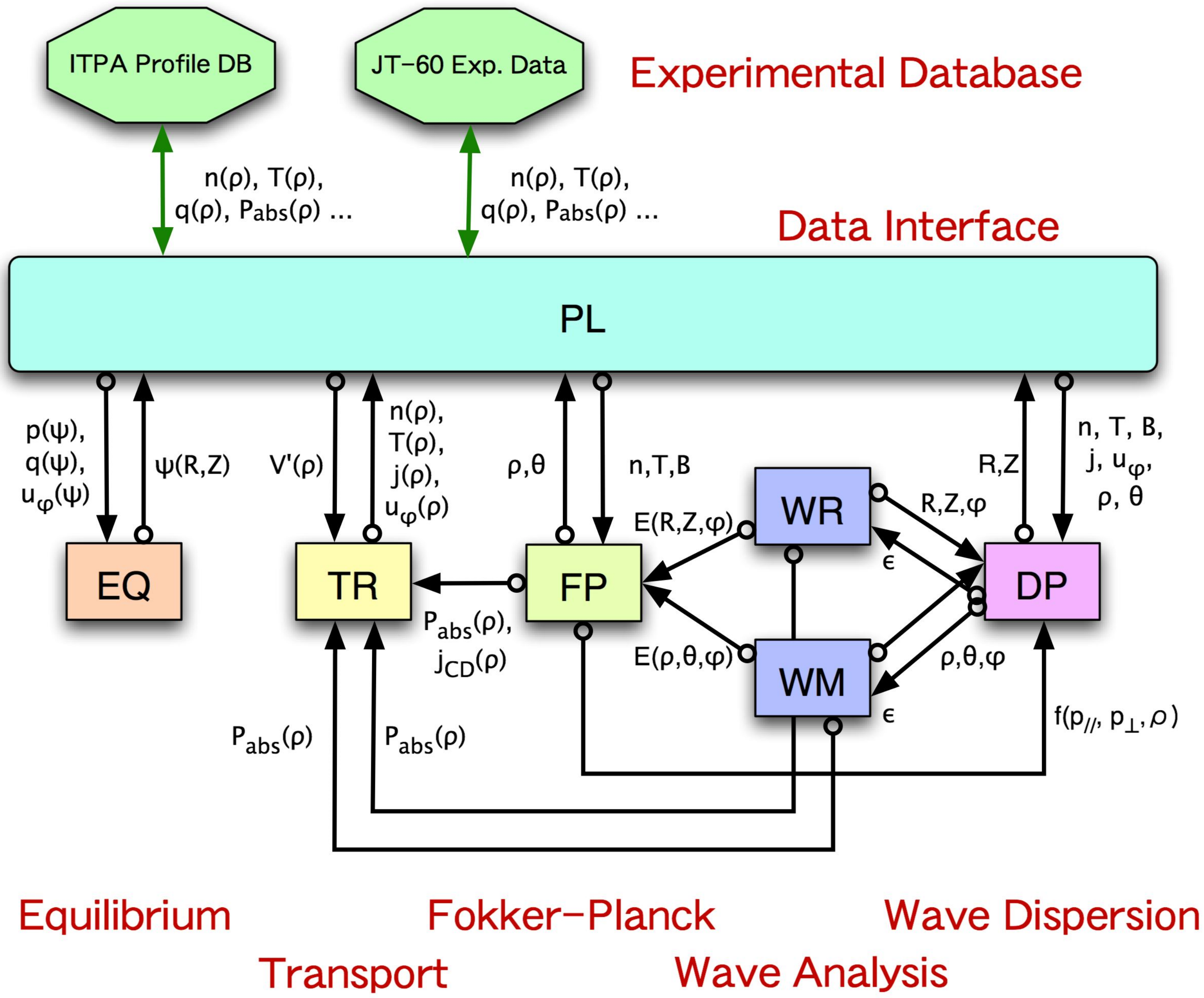
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(v)$
PL	**Data Interface**	Data conversion, Profile database
LIB	**Libraries**	

Associated Libraries

GSAF	2D Graphic library for X Window and EPS
GSGL	3D Graphic library using OpenGL

All developed in Kyoto U

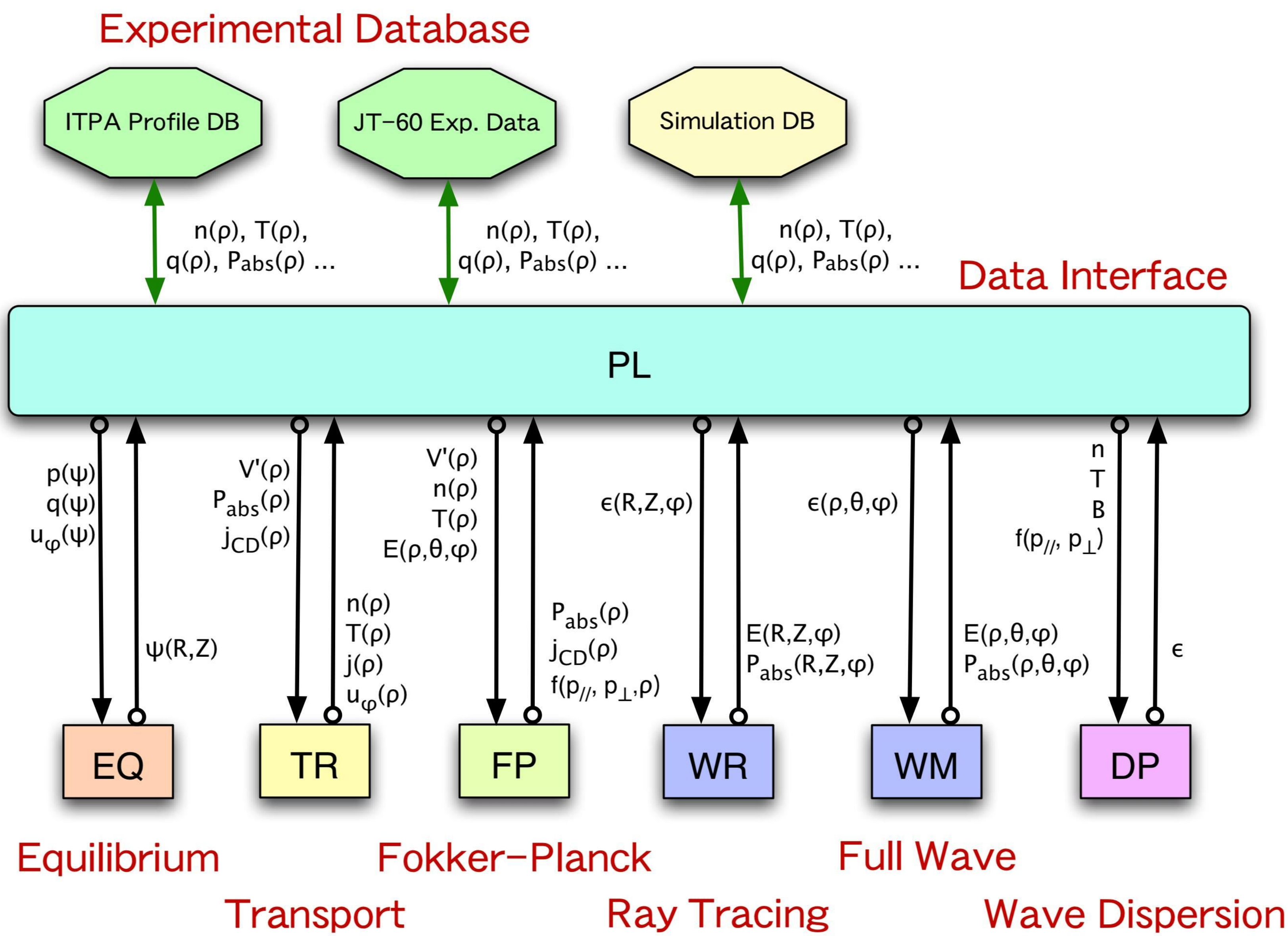
Original Structure of TASK



Under Development

- **New Modules**
  - **`EX`**: 2D equilibrium with free boundary
  - **`TX`**: Transport analysis based on flux-averaged fluid equation
  - **`WA`**: Global linear stability analysis
  - **`WI`**: Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)
- **Extension to 3D Helical System**
  - **3D Data Structure**
  - **3D Equilibrium**: VMEC, HINT
  - **Wave Analysis**: Already 3D
  - **Transport Analysis**: New transport model
- **New Modular Structure**

New Modular Structure of TASK



Transport Analysis

- **Level of Analysis**:
  - **TASK/TR**: Diffusive transport equation:
    — Flux-Gradient relation
    — Conventional transport analysis
  - **TASK/TX**: Dynamical transport equation:
    — Flux-averaged fluid equation
    — Plasma rotation and transient phenomena
  - **TASK/FP**: Kinetic transport equation:
    — Bounce-averaged Fokker-Plank equation
    — Modification of momentum distribution

Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
    — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
    — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
  - UFILE (ITPA profile DB)

Turbulent Transport Model

- **Development of Robust Transport Model**
  - L-mode confinement time scaling
  - Large transport near the plasma edge in L-mode
  - H-mode confinement time scaling for given edge temperature
  - Formation of internal transport barrier
  - Experimentally observed profile
  - Behavior of fluctuation
- **Validation of the Model**
  - Profile Database (ITPA)
  - Large-scale Turbulence Simulation

CDBM Turbulence Model

- **Marginal Stability Condition** $(\gamma = 0)$

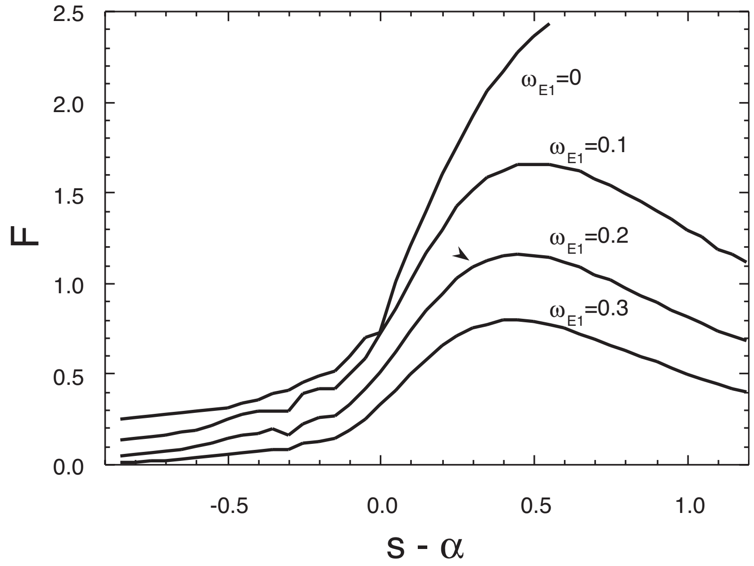
$$\chi_{\rm TB} = F(s, \alpha, \kappa, \omega_{\rm E1})\,\alpha^{3/2}\,\frac{c^2}{\omega_{\rm pe}^2}\,\frac{v_{\rm A}}{qR}$$

Magnetic shear	$s \equiv \dfrac{r}{q}\dfrac{{\rm d}q}{{\rm d}r}$
Pressure gradient	$\alpha \equiv -q^2 R \dfrac{{\rm d}\beta}{{\rm d}r}$
Magnetic curvature	$\kappa \equiv -\dfrac{r}{R}\left(1 - \dfrac{1}{q^2}\right)$
$E \times B$ **rotation shear**	$\omega_{\rm E1} \equiv \dfrac{r^2}{s v_{\rm A}}\dfrac{{\rm d}}{{\rm d}r}\dfrac{E}{rB}$

- **Weak and negative magnetic shear,**
  Shafranov shift and
  $E \times B$ **rotation shear**

reduce thermal diffusivity.

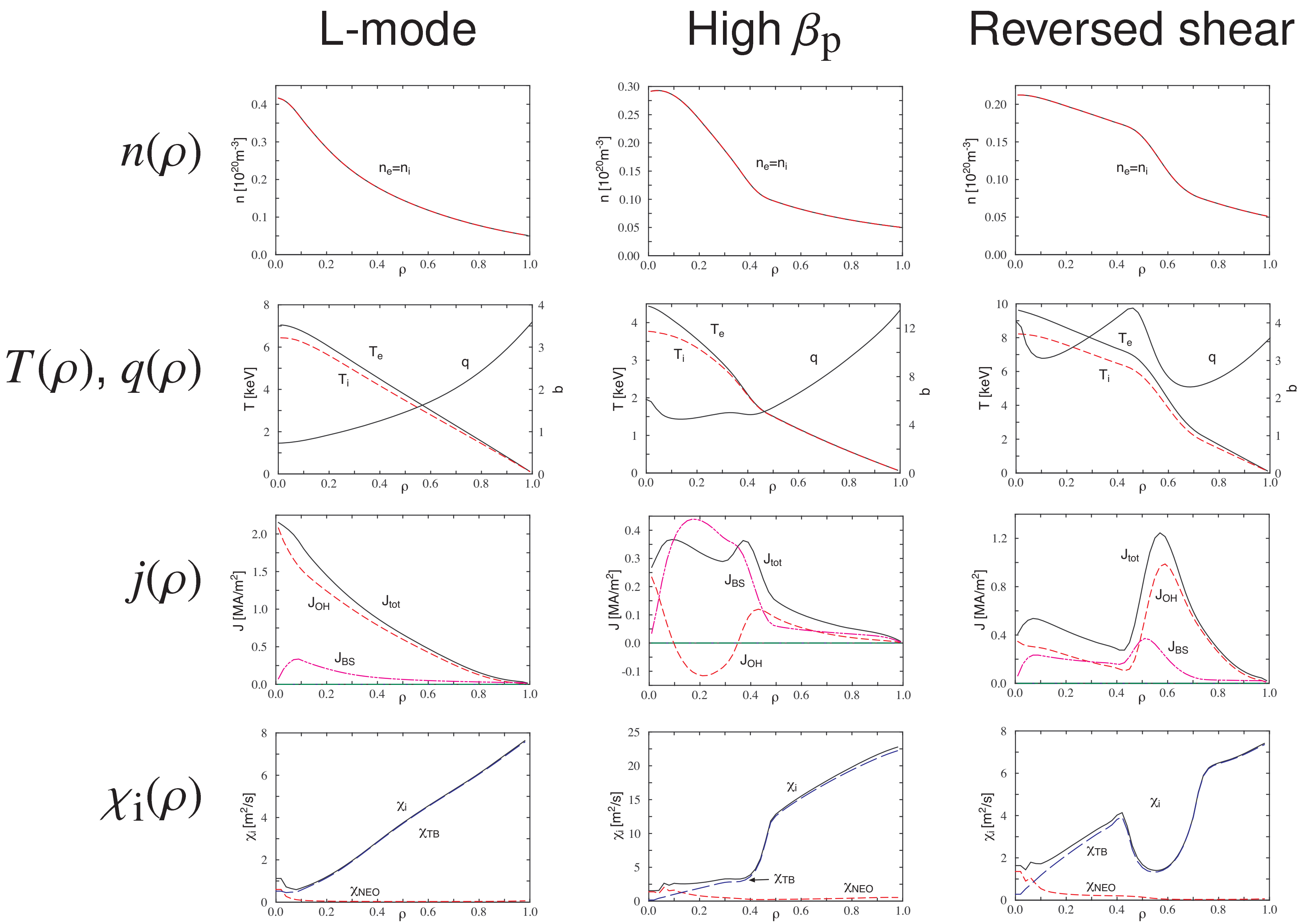
$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\rm E1})$



Fitting Formula

$$F = \begin{cases} \dfrac{1}{1 + G_1\omega_{\rm E1}^2}\,\dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for}\quad s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1 + G_1\omega_{\rm E1}^2}\,\dfrac{1 + 9\sqrt{2}\,s'^{5/2}}{\sqrt{2}(1 - 2s' + 3s'^2 + 2s'^3)} & \text{for}\quad s' = s - \alpha > 0 \end{cases}$$

Typical Profile (CDBM+NCLASS)



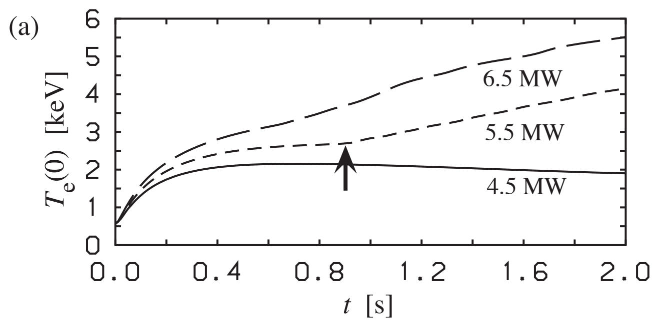
Effect of $E \times B$ Rotation Shear

- **Reduction of transport** due to small s and large α: $F(s, \alpha, \kappa)$

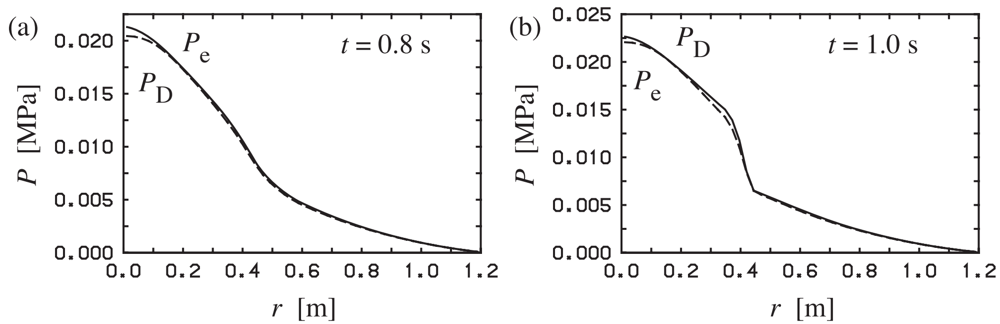
  $\Longrightarrow$ **Rapid increase of rotation shear**: $1/[1 + G(s, \alpha)\omega_{E1}^2]$

  $\Longrightarrow$ **Transition to enhanced ITB**

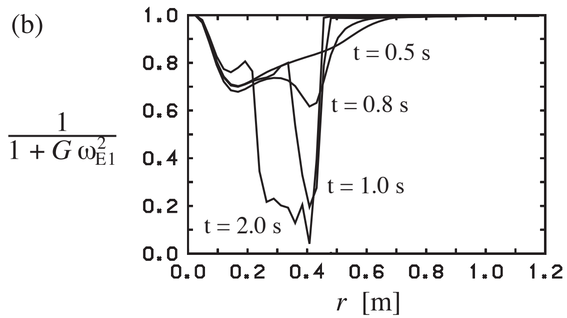
Time evolution of $T_e(0)$



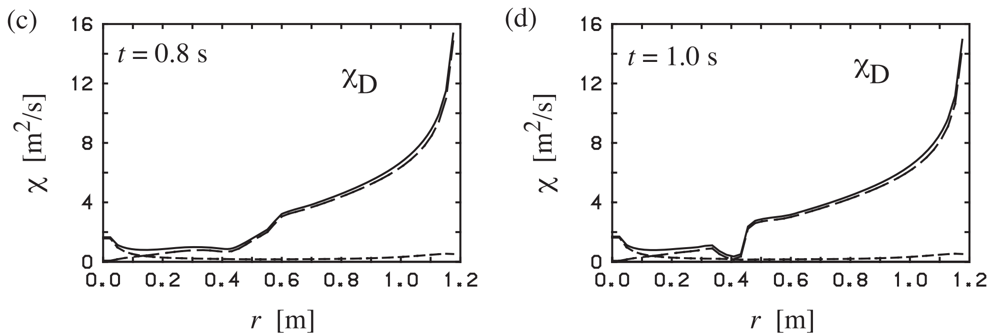
Pressure Profile Before and After Transition



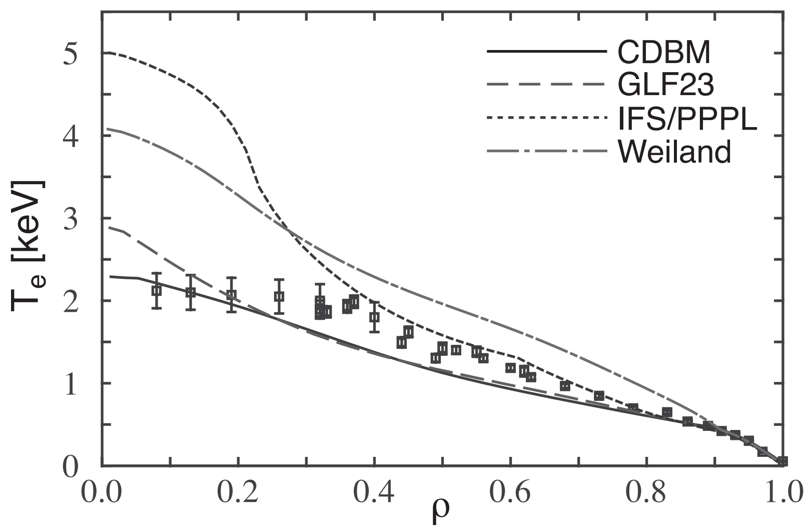
Rapid Change of Rotation Shear

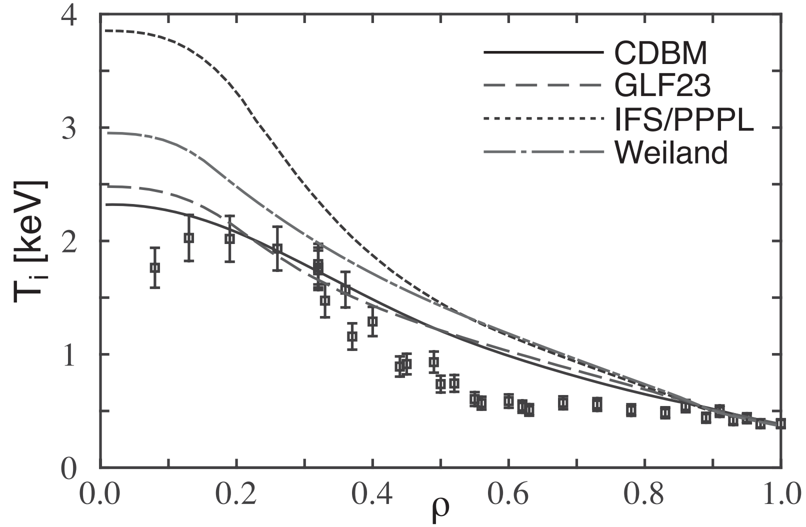


Thermal Diffusivity Before and After Transition



Heat transport simulation for the L-mode shot #82188 on DIII-D tokamak





- **Incidental agreement of CDBM and GLF23 results**
- **Fairly good agreement with experiments**

Comparison with JET Experiment

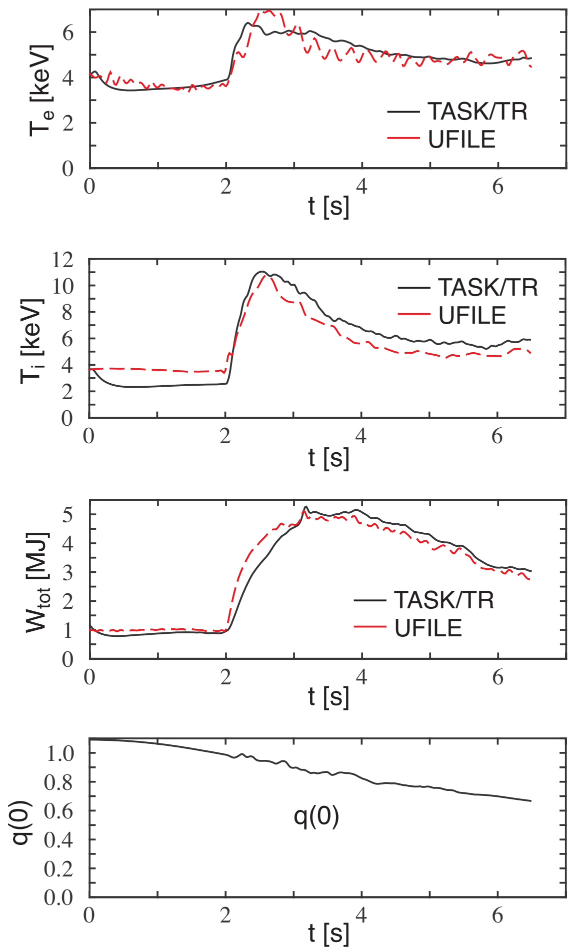
- **Shot number: 19691**

T_{e0}

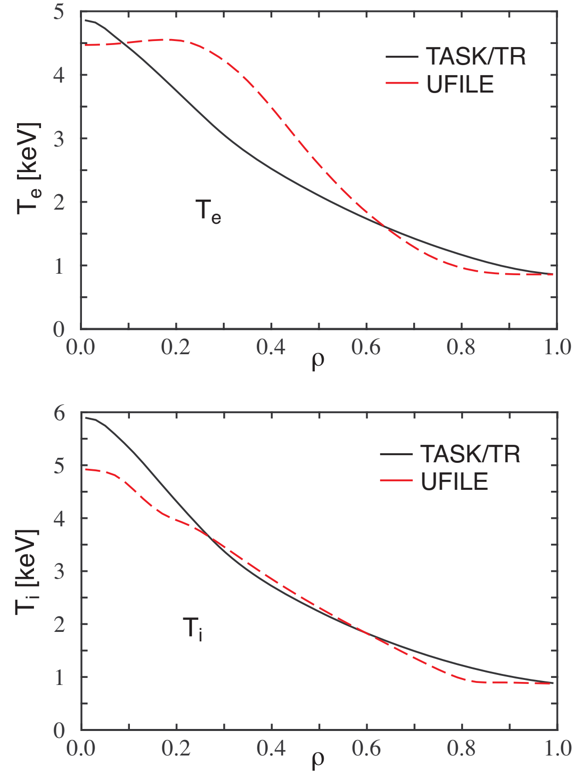
T_{i0}

W_{tot}

q_0



T_e and T_i

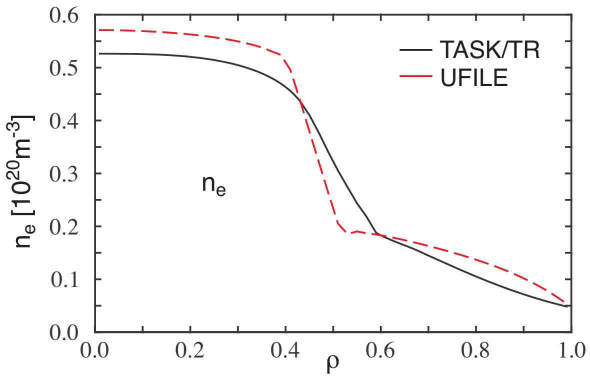


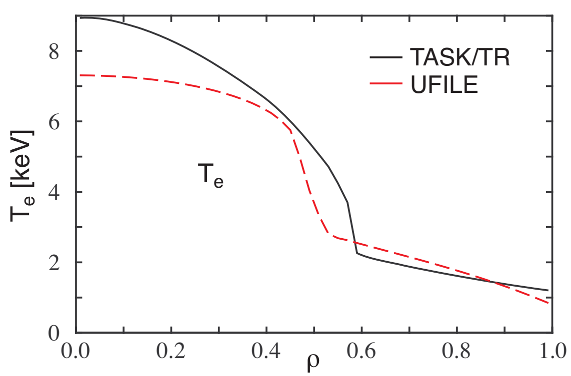
- **Sawtooth relaxation slightly improves T_e profile.**

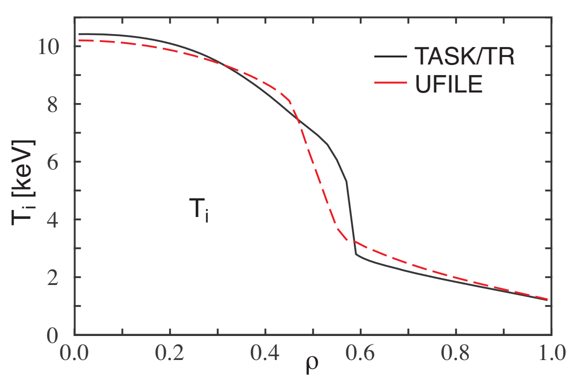
Comparison with JT-60 Experiment

- **Reversed Shear Configuration**
  - **Shot number: 29728**
  - Profiles q, P_e, P_i: given
  - Metric data: given
  - Edge density and temperature: given
  - Transport model: Sauter + CDBM(with $E \times B$ rotation)

$n_\mathrm{e}(\rho)$ $T_\mathrm{e}(\rho)$ $T_\mathrm{i}(\rho)$

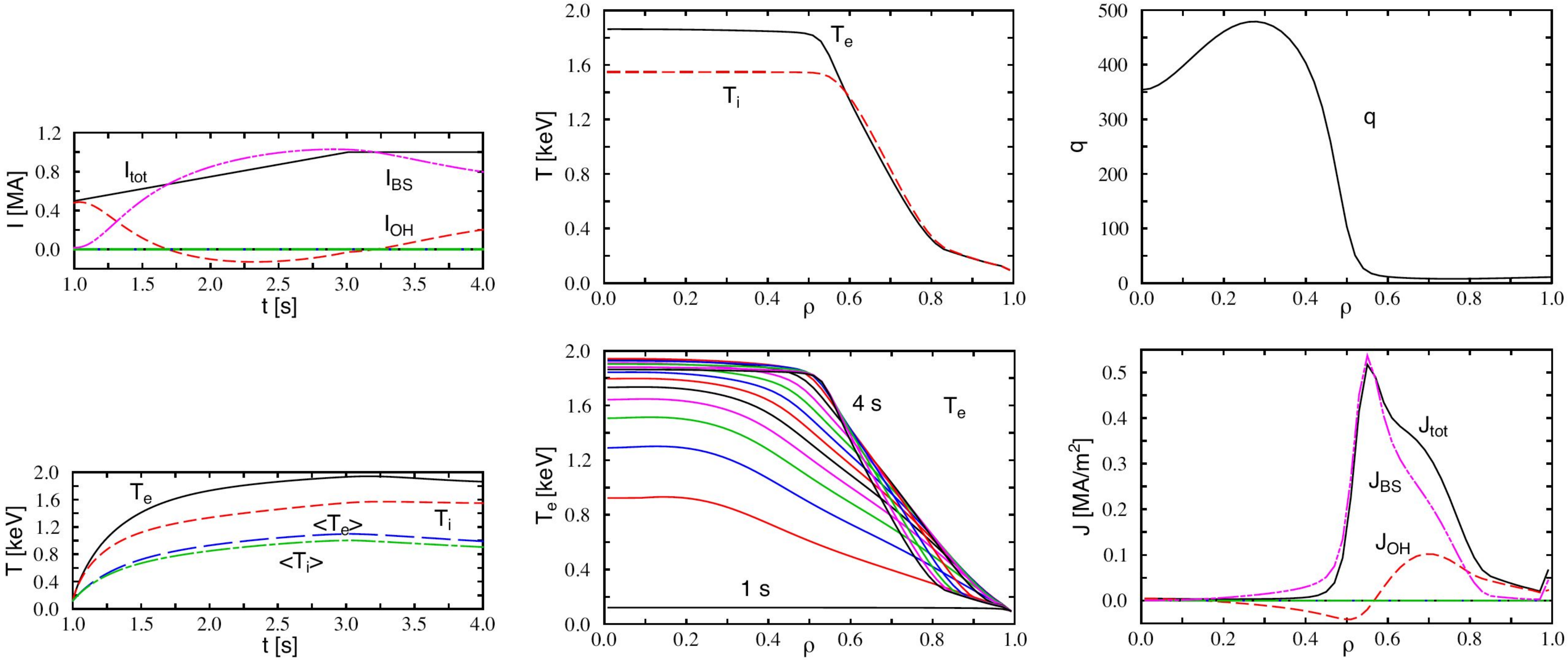






Simulation of Current Hole Formation

- Current ramp up: $I_\mathrm{p} = 0.5 \longrightarrow 1.0\,\mathrm{MA}$
- Moderate heating: $P_\mathrm{H} = 6.5\,\mathrm{MW}$
- **Current hole** is formed.



Modeling of ETB Formation

- **Transport Simulation including Core and SOL Plasmas**
- **Role of Separatrix**
  - Closed magnetic surface $\Longleftrightarrow$ Open magnetic field line
  - Difference of dominant transport process
- **Radial Electric Field**
  - Poloidal rotation, Toroidal rotation
  - Polarization current
  - Poisson equation
- **Atomic Processes**
  - Ionization, Charge exchange, Recycling

Dynamical Transport Model: TASK/TX

- **1D Transport code** (TASK/TX)   *Ref. Fukuyama et al.*
- **Two fluid equation for electrons and ions**
  - Flux surface average
  - Coupled with Maxwell equation
  - Neutral diffusion equation
- **Neoclassical transport**
  - Included as a poloidal viscosity term
  - Diffusion, resistivity, bootstrap current, Ware pinch
- **Anomalous transport**
  - Current diffusive ballooning mode
  - Ambipolar diffusion through poloidal momentum transfer
  - Perpendicular viscosity

Model Equation (1)

- **Fluid equations** (electrons and ions)

$$\frac{\partial n_s}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r n_s u_{sr}) + S_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{sr}) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr}^2) + \frac{1}{r} m_s n_s u_{s\theta}^2 + e_s n_s(E_r + u_{s\theta}B_\phi - u_{s\phi}B_\theta) - \frac{\partial}{\partial r} n_s T_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{s\theta}) = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 m_s n_s u_{sr} u_{s\theta}) + e_s n_s(E_\theta - u_{sr}B_\phi) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^3 n_s m_s \mu_s \frac{\partial}{\partial r}\frac{u_{s\theta}}{r}\right)$$

$$-\nu^{\mathrm{NC}} m_s n_s u_{s\theta} - \sum_{s'} \nu_{\mathrm{ss}'}^{\mathrm{C}} m_s n_s (u_{s\theta} - u_{s'\theta}) + F_{s\theta}^{\mathrm{W}} - \nu_s^{\mathrm{CX}} m_s n_s u_{s\theta} - \nu_s^{\mathrm{L}} m_s n_s u_{s\theta}$$

$$\frac{\partial}{\partial t}\left(m_s n_s u_{s\phi}\right) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr} u_{s\phi}) + e_s n_s(E_\phi + u_{sr}B_\theta) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_s m_s \mu_s \frac{\partial}{\partial r} u_{s\phi}\right)$$

$$-\nu^{\mathrm{NC}} m_s n_s u_{s\phi} - \sum_{s'} \nu_{\mathrm{ss}'}^{\mathrm{C}} m_s n_s (u_{s\phi} - u_{s'\phi}) + F_{s\phi}^{\mathrm{W}} - \nu_s^{\mathrm{CX}} m_s n_s u_{s\phi} - \nu_s^{\mathrm{L}} m_s n_s u_{s\phi}$$

$$\frac{\partial}{\partial t}\frac{3}{2} n_s T_s = -\frac{1}{r}\frac{\partial}{\partial r} r\left(\frac{5}{2} u_{sr} n_s T_s - n_s \chi_s \frac{\partial}{\partial r} T_{\mathrm{e}}\right) + e_s n_s(E_\theta u_{s\theta} + E_\phi u_{s\phi}) - \sum_{s'} \nu_{\mathrm{ss}'}^{\mathrm{CT}} n_s (T_s - T_{\mathrm{s}'}) - \nu_s^{\mathrm{LT}} n_s T_s + P_s^{\mathrm{H}}$$

Model Equation (2)

- **Neutral Transport**

$$\frac{\partial n_0}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(-rD_0\frac{\partial n_0}{\partial r}\right) + S_0$$

- **Maxwell equations**

$$\frac{1}{r}\frac{\partial}{\partial r}(rE_r) = \frac{1}{\epsilon_0}\sum_s e_s n_s$$

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial E_\phi}{\partial r},$$

$$\frac{1}{c^2}\frac{\partial E_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) - \mu_0 \sum_s n_s e_s u_{s\phi}$$

$$\frac{\partial B_\phi}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rE_\phi)$$

$$\frac{1}{c^2}\frac{\partial E_\theta}{\partial t} = -\frac{\partial}{\partial r}B_\phi - \mu_0 \sum_s n_s e_s u_{s\theta},$$

Transport Model (1)

- **Neoclassical transport**
  - Viscosity force arises when plasma rotates in the poloidal direction.
  - Banana-Plateau regime

$$F_{s\theta}^{\mathrm{NC}} = -\sqrt{\pi} q^2 n_s m_s \frac{v_{\mathrm{Ts}}}{qR} \frac{\nu_s^*}{1+\nu_s^*} u_{s\theta}$$

$$\nu_{\mathrm{s}}^* \equiv \frac{\nu_s qR}{\epsilon^{3/2} v_{\mathrm{Ts}}}$$

- **This poloidal viscosity force induces**
  - Neoclassical radial diffusion
  - Neoclassical resistivity
  - Bootstrap current
  - Ware pinch

Transport Model (2)

- **Turbulent Diffusion**
  - Poloidal momentum exchange between electron and ion through the turbulent electric field
  - Ambipolar flux (electron flux = ion flux)

$$F_{\mathrm{i}\theta}^{\mathrm{W}} = - F_{\mathrm{e}\theta}^{\mathrm{W}}$$

$$= - ZeB_\phi n_\mathrm{i} D_\mathrm{i} \left[-\frac{1}{n_\mathrm{i}} \frac{dn_\mathrm{i}}{dr} + \frac{Ze}{T_\mathrm{i}} E_r - \langle \frac{\omega}{m} \rangle \frac{ZeB_\phi}{T_\mathrm{i}} - \left(\frac{\mu_\mathrm{i}}{D_\mathrm{i}} - \frac{1}{2} \right) \frac{1}{T_\mathrm{i}} \frac{dT_\mathrm{i}}{dr} \right]$$

- **Perpendicular viscosity**
  - Non-ambipolar flux (electron flux ≠ ion flux): $\mu_\mathrm{s} = \mathrm{constant} \times D$
- **Diffusion coefficient** (proportional to $|E|^2$)
  - Current-diffusive ballooning mode turbulence model

Modeling of Scrape-Off Layer Plasma

- **Particle, momentum and heat losses along the field line**
  - Decay time

$$\nu_{\rm L} = \begin{cases} 0 & (0 < r < a) \\ \dfrac{C_{\rm s}}{2\pi r R\{1 + \log[1 + 0.05/(r-a)]\}} & (a < r < b) \end{cases}$$

  - **Electron source term**

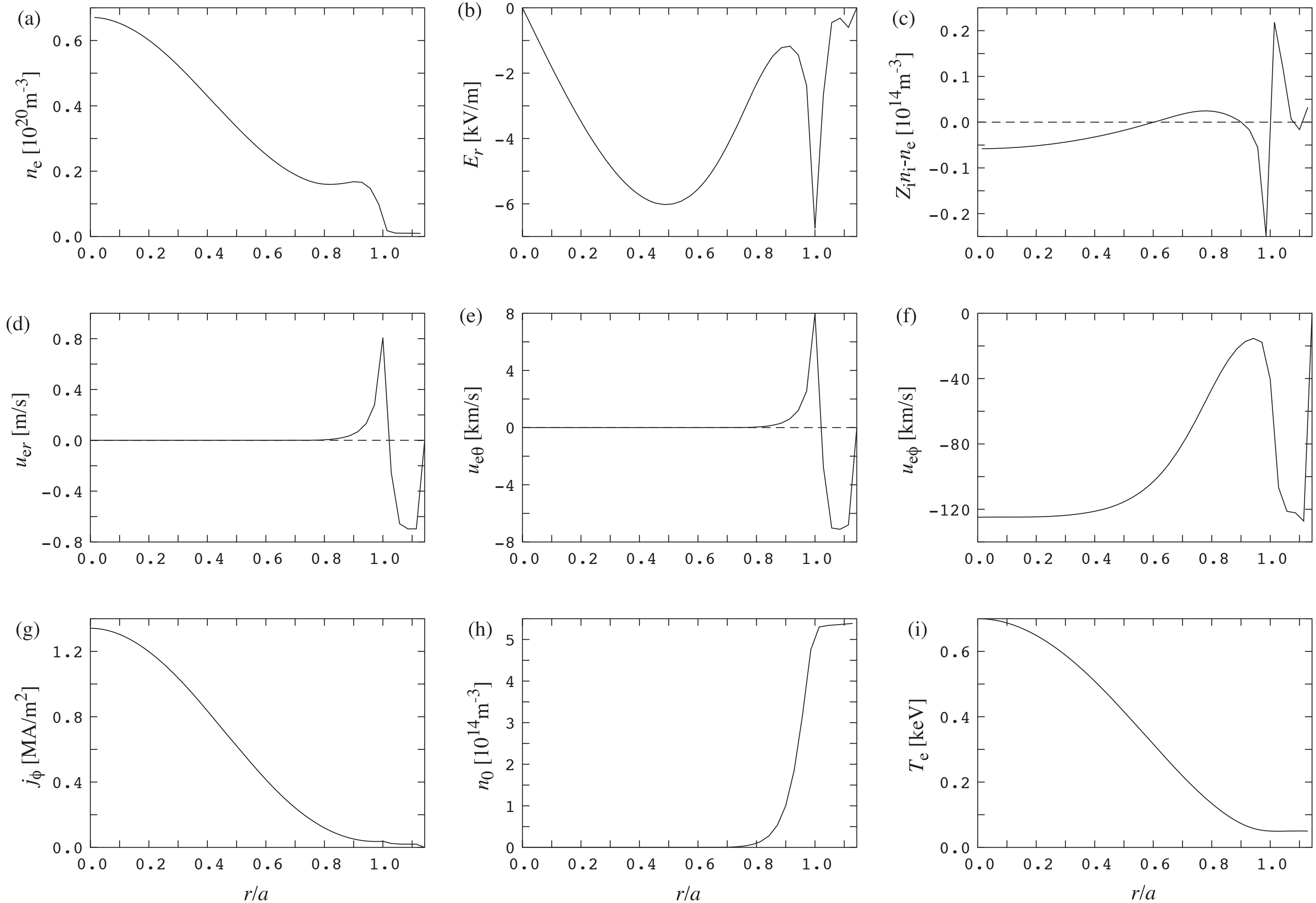
$$S_{\rm e} = n_0 \langle \sigma_{\rm ion} v \rangle n_{\rm e} - \nu_{\rm L}(n_{\rm e} - n_{\rm e,div})$$

- **Recycling from divertor**
  - Recycling rate: $\gamma_0 = 0.8$
  - Neutral source

$$S_0 = \frac{\gamma_0}{Z_{\rm i}} \nu_{\rm L}(n_{\rm e} - n_{\rm e,div}) - \frac{1}{Z_{\rm i}} n_0 \langle \sigma_{\rm ion} v \rangle n_{\rm e} + \frac{P_{\rm b}}{E_{\rm b}}$$

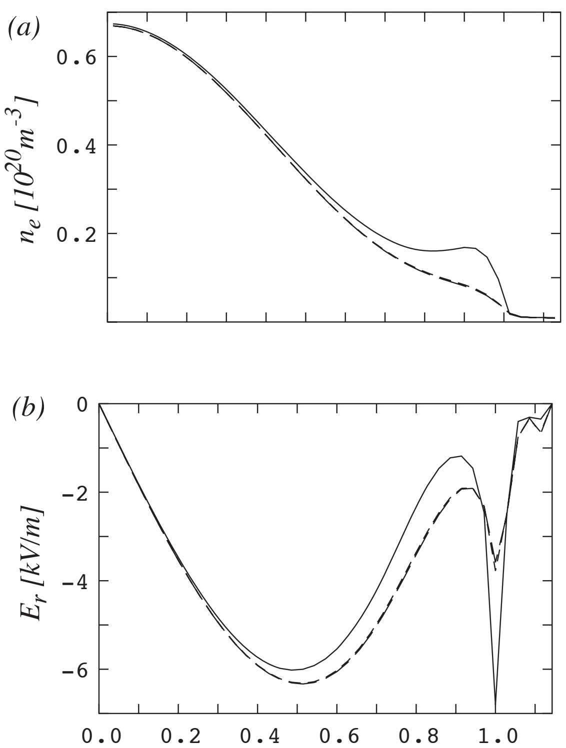
- **Gas puff from wall**

Typical Profiles without Turbulent Transport

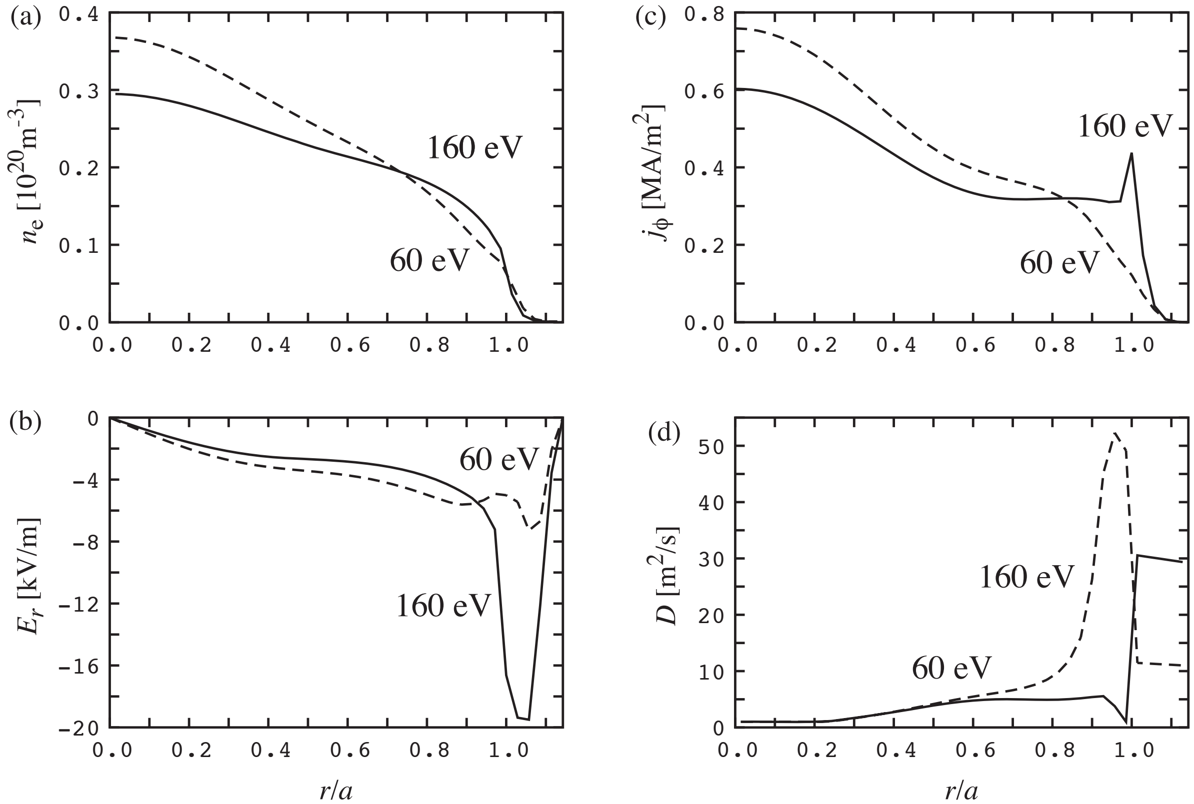


Typical Profiles

$D_{\mathrm{TB}} = 0$

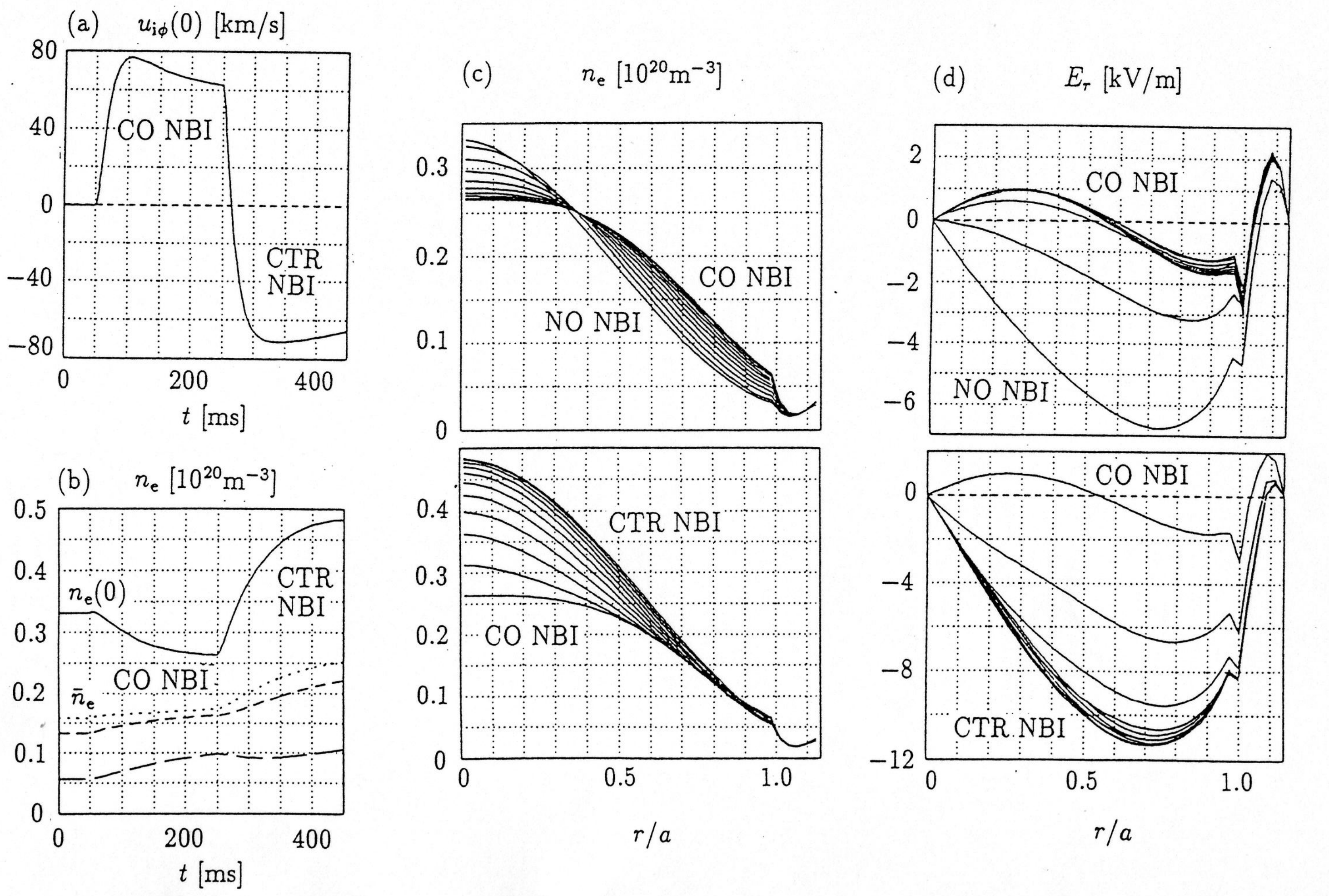


Edge Temperature Dependence



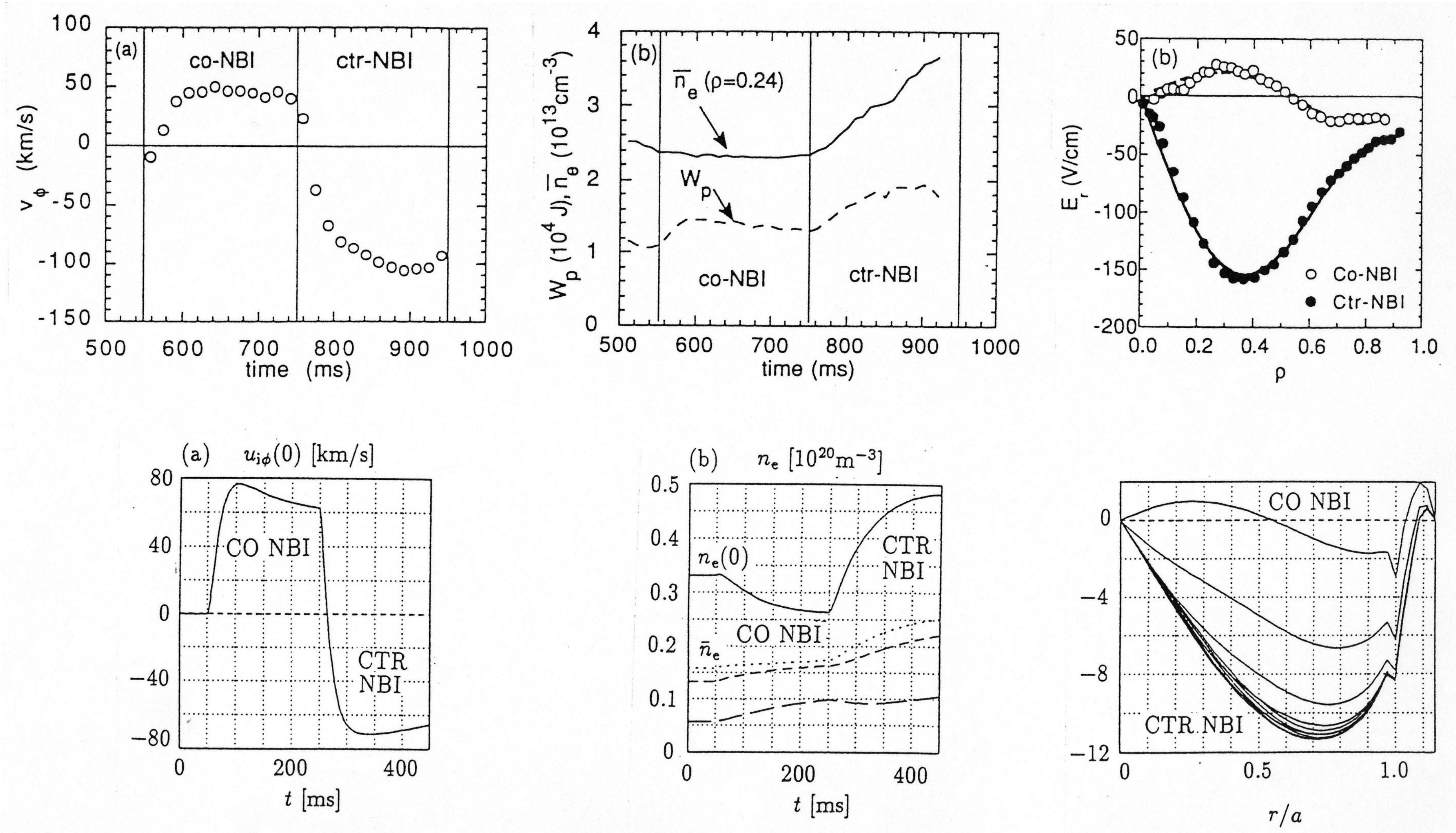
Simulation of plasma rotation and radial electric field

- **JFT-2M parameter**: NBI co-injection $\longrightarrow$ counter-injection
- Toroidal rotation $\Longrightarrow$ Negative E_r $\Longrightarrow$ Density peaking
- **TASK/TX**: Particle Diffusivity: $0.3\,\mathrm{m^2/s}$, Ion viscosity: $10\,\mathrm{m^2/s}$



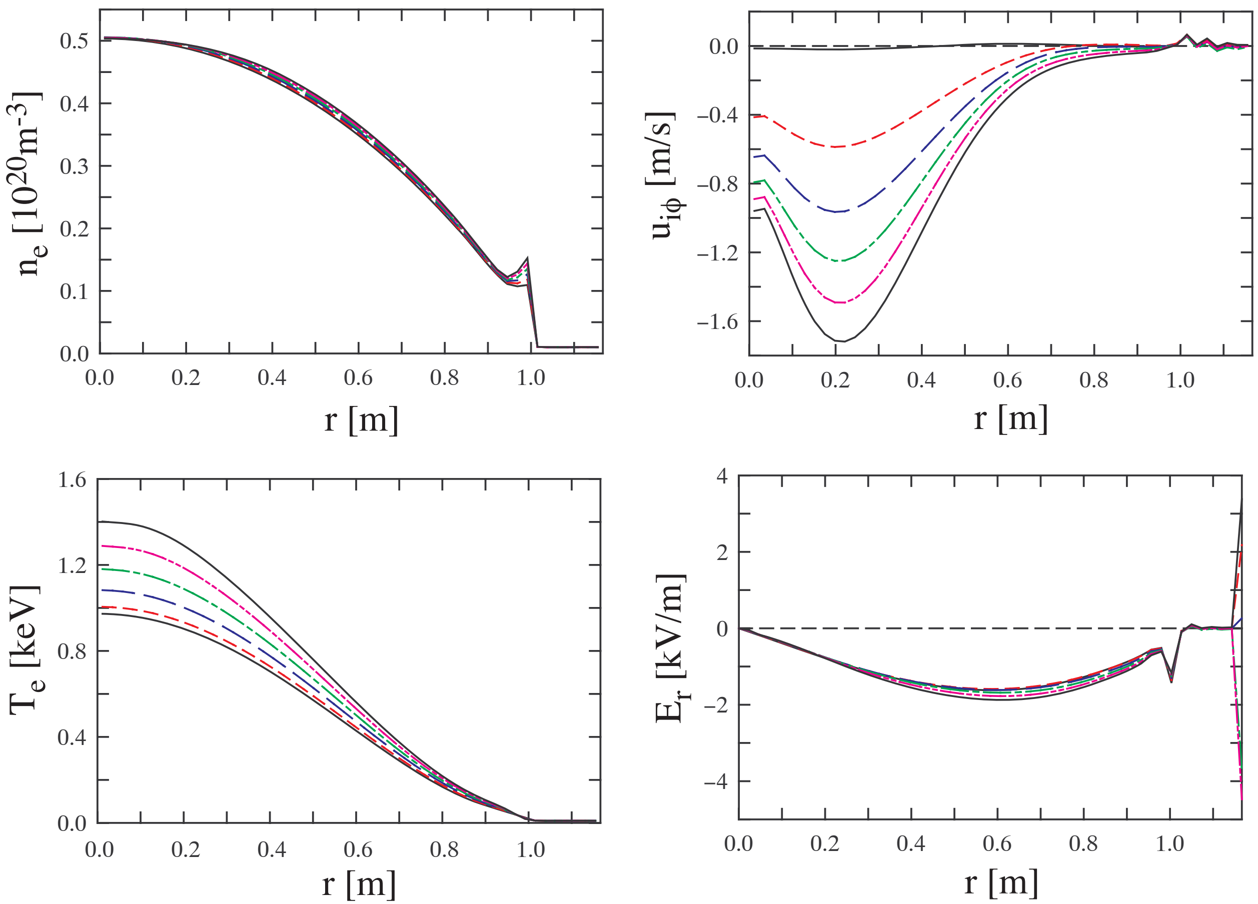
Comparison with JFT-2M Experiment

- **JFT-2M Experiment**: **Ida et al.: Phys. Rev. Lett. 68 (1992) 182**
- Good agreement with experimental observation



Transport Modeling in Helical Plasma

- **Neoclassical toroidal viscosity**
- **Negative magnetic shear**
- **Preliminary Result**
  - **NBI heating** ($P = 5\,\mathrm{MW}$) : Order of magnitude slower rotation



TASK2005 (Documentation)

1. **Introduction**
2. **TASK code** (Modular structure, How to get, install, and use)
3. **EQ: Equilibrium** — **JAERI Rep 2004a+α**
4. **TR: Transport** — **JAERI Rep 2004a**
5. **DP: Wave Dispersion Relation** — **Lecture note**
6. **WR: Ray and Beam Tracing** — **JAERI Rep 2003a**
7. **WM: Full Wave Analysis** — **JAERI Rep 2002b**
8. **FP: Momentum Distribution Function** — **JAERI Rep 2003a**
9. **PL: Data Interface**
10. **Integrated Simulation**
11. **Works in Progress**
12. **Appendix: GSAF: Graphic Library**

Contents

Summary

- CDBM transport model reproduces various kinds of improved confinement modes associated with **ITB formation**.
- **ETB formation** in H-mode was studied by using surface-averaged fluid equations in both core and SOL plasmas. The change of transport mechanism across the separatrix generates the radial electric field at the edge and suppress the transport.
- In **toroidal helical plasmas**, neoclassical toroidal viscosity impedes toroidal rotation and affects the transport. Preliminary result was presented.
- **Further improvement in transport modeling is required:**
  - Turbulen transport model (zonal flow, E_r, ballooning mode)
  - Dynamical transport equations (numerical stability)
  - Coupling with SOL plasmas (open-field structure)